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Hull Material Evaluation for Navy 44 Sail Training Vessel

Abstract

Material characterization tests were performed at the US Naval Academy to identify a toughened laminate for the new Navy 44-foot sail training vessels. After preliminary analysis using classical lamination theory, four different cores, five laminates and seven resin systems were tested in UV exposure, four-point bending, lateral panel pressure, and simulated bow impact. Results showed substantial improvements in strength, toughness, cost and weight were possible over the existing laminate, with the lightest acceptable laminate yielding a weight savings equivalent to 3.5% of the vessel's displacement.

Introduction

The McCurdy and Rhodes Navy 44 sloop is the latest in a series of offshore–capable vessels used for midshipman seamanship and navigation training at the United States Naval Academy(Navy 44 2000). Overbuilt by yacht standards, the Navy 44 is a heavily-used platform

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14. ABSTRACT
Material characterization tests were performed at the US Naval Academy to identify a toughened laminate for the new Navy 44-foot sail training vessels. After preliminary analysis using classical lamination theory, four different cores, five laminates and seven resin systems were tested in UV exposure, four-point bending, lateral panel pressure, and simulated bow impact. Results showed substantial improvements in strength, toughness, cost and weight were possible over the existing laminate, with the lightest acceptable laminate yielding a weight savings equivalent to 3.5% of the vessel?s displacement.

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designed to take the rigors of midshipmen training, as well as serve as a racing platform for the Varsity Offshore Sailing Team. From Spring through Fall, all 20 boats are used five to seven days a week and down time of any boat significantly impacts the operation schedule. As the current vessels are nearing the end of their service life, an investigation into alternate construction materials was undertaken to determine if materials developed over the last two decades could provide a more durable vessel.

While the Navy 44 is not a combat platform in the traditional sense, it must be able to withstand abuse from collisions, docking mishaps, and the occasional grounding. Design criteria range from regulatory to practical. So as to participate in offshore races, the minimum structural design standards are those of the International Measurement System (IMS) (IMS 2000) and the American Bureau of Shipping (ABS) Guide for Building and Classing Offshore Racing Yachts (ABS 1986). For practical reasons the boats exceed these standards by a large margin. A review of all stakeholders indicated that the new boats should be at least as “rugged” as the current design, easily repairable, and must be able to maintain a high-quality surface finish. With the reduction in naval maintenance personnel, a material system that would localize damage and hence minimize repair costs was highly desirable. Like most vessels, a solution that reduced weight would be beneficial and cost was a factor.

The current topside hull laminate represents mid-80’s technology for a tough fiberglass (E-glass) laminate. Two layers of 24 oz/yd^2 knitted fabrics combined with 1oz/ft^2 random-oriented mat sandwiched a 6 lb/ft^3 Airex (linear PVC) core. A high-elongation vinyl ester resin served as the binding matrix and the outermost surface included a 1.5 oz/ft^2 mat cloth to provide a smooth surface.

The project began with a review of potential improved materials, discussions with material suppliers and a preliminary laminate analysis using classical laminated plate theory (CLT). A test matrix was then developed of the major variables and manufacturers were contacted for raw materials. Coupons and panels were then fabricated in the Naval Academy’s Model Shop and tested in the Academy’s structures labs.

Laminated Plate Theory Analysis

CLT analysis uses Hooke's Law to develop stress-strain relationships for multi-ply laminates. For most laminates a plane stress assumption is acceptable and requires three moduli (E_x, E_y and G_{xy}) and the inplane Possion's Ratio (ν_{xy}). Failure analysis requires five strength parameters (σ_{xt}, σ_{xc}, σ_{yt}, σ_{yc}, τ_{xy}) and a failure criterion. The matrix math is relatively straight forward, but for ease of analysis, a share-ware program, "The Laminator" was used (Lindell 1999).

The current Navy 44 hull laminate was compared to several possible laminates. Both in-plane and out-of-plane load conditions were analyzed with each laminate to obtain the lowest factor of safety using the Tsai-Wu quadratic failure criterion (Tsai and Hahn 1980). In the bending case the innermost tensile ply was predicted to fail first. The exception was the Kevlar plies which failed first in compression.

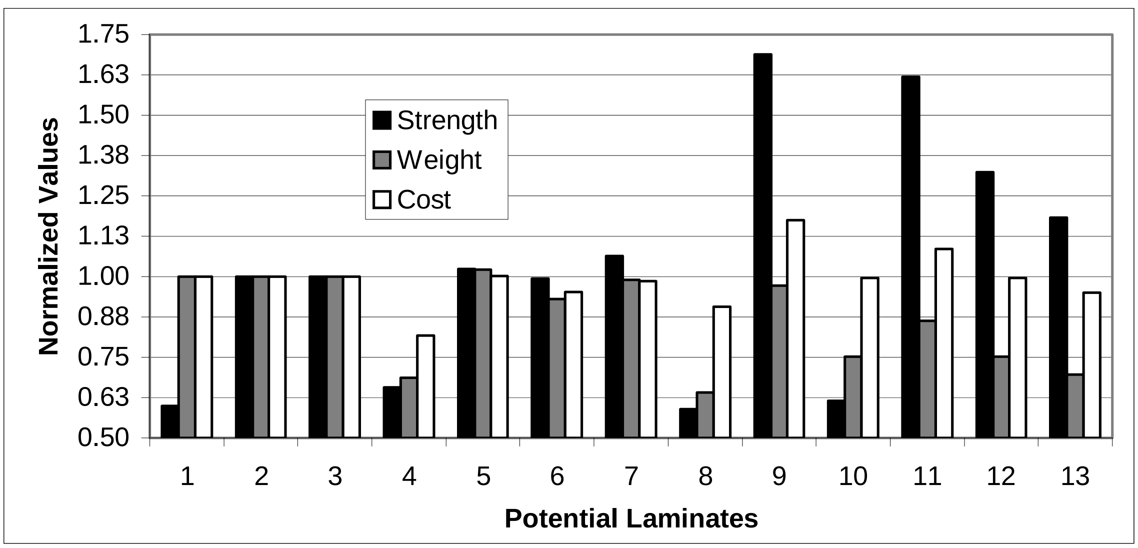
Along with the strength analysis, a weight and cost analysis was performed to foresee which future laminates should be considered in further strength and impact testing. Results can be seen in Figure 1, where the strength, weight and cost of the top thirteen laminates are normalized to the current Navy 44 laminate, laminate #2. Table 1 shows the laminate details. The "Plies" column describes the number and type of cloth layers. Each ply is separated by a slash. Two digit numbers refer to the ply areal weight, for instance an "18" refers to a cloth of weight 18 oz/yd^2 with the fibers oriented 0/90. "1.5" refers to a 1.5 oz/ft^2 random oriented mat and "2410" is a combination fabric with 24 oz/yd^2 0/90 and 1.0 oz/ft^2 mat. All the cores were 0.75 inch thickness.

The major result from this analysis included the desire to remove the mat layers, which due to their relatively low tensile strength led to early failure and low weight efficiency. Although traditional polyester laminates often use alternating cloth and mat layers so that the resin-rich mat layers will increase delamination resistance, vinyl ester laminates have not seen the same problems. Based on these results a test matrix was developed which included laminates comparing core materials, specific resin systems and different fiber formats.

Table 1: Potential Laminates Used in CLT Analysis

Number	Name	Plies	Core	Resin
1	Old-poly	1.5/2410/2410/core/2410/2410	Airex(62.80)	Polyester
2	Old-1a	1.5/2410/2410/core/2410/2410	Airex(62.80)	Vinylester
3	Old-1b	1.5/2410/2410/core/2410/2410	Airex(63.80)	Vinylester
4	New-v1	24/24/core/24/24:	Airex(63.80)	Vinylester
5	New-v2	18/24/24/24/core/24/24/24	Airex(63.80)	Vinylester
6	New-v3	24/24/24/core/24/24/24	Airex(63.80)	Vinylester
7	New-v4	18/24/18/18/core/18/18/24/18	Airex(63.80)	Vinylester
8	New-e1	24/24/core/24/24	Airex(63.80)	Epoxy
9	New-e2	24/24/24/24/core/24/24/24	Airex(63.80)	Epoxy
10	New-e3	24/24/24/core/24/24	Airex(63.80)	Epoxy
11	New-e4	24/24/24/core/24/24/24	Airex(63.80)	Epoxy
12	New-e5	18/24/18/core/18/24/18	Airex(63.80)	Epoxy
13	New-e6	18/18/18/core/18/18/18	Airex(63.80)	Epoxy

Figure 1: Normalized Strength, Weight, and Cost Analysis of Potential Laminates



Experimental

The final test matrix was driven by the CLT results and the manufacturers' willingness to donate material for testing. For cost reasons E-glass was chosen as the fiber, and manufacturers were contacted for samples of their "toughest" core or resin systems. Final laminates were specified that appeared to bracket the two limiting cases: a laminate of nearly equal weight but increased toughness, and a laminate of equal toughness, but reduced weight. The final laminate test matrix is shown in Table 2. All the laminates were symmetrical except as indicated in the "Plies" column, where colons separate the outer skin from the inner skin layup. The thinner skin is the inside of the hull. Laminate "C0" is the current laminate. A "K" refers to the addition of one layer of #500 (5 oz/yd^2) Kevlar cloth. The vinyl ester laminates had an added layer of 0.75 oz/ft^2 random oriented mat on the outer surface as a "veil" cloth. The reasons for this are described in the next section.

Table 2: Test Matrix

Name	Plies	Core	Resin
C0	1.5/2410/2410/core/2410/2410	Airex	Corezyn 8117
C1	18/18/18/core/18/18/18	Airex	Proset 125
C2	18/18/18/core/18/18/18	Divinycell	Proset 125
C3	18/18/18/core/18/18/18	Corecell	Proset 125
C4	18/18/18/core/18/18/18	WestCore	Proset 125
L1	18/24/18/core/18/24/18	Airex	Proset 125
L2	18/24(45°)/18/core/18/24(45°)	Airex	Proset 125
L3	24/24/24/24/core/24/24/24	Airex	Proset 125
L4	18/K/18/18/core/18/18/K/18	Airex	Proset 125
R1	18/18/18/core/18/18/18	Airex	Proset 117
R2	18/18/18/core/18/18/18	Airex	MAS
R3	18/18/18/core/18/18/18	Airex	USC 2000
R4	0.75/18/18/18/core/18/18/18	Airex	Corezyn 8117
R5	0.75/18/18/18/core/18/18/18	Airex	Derakane 8084
R7	18/18/18/core/18/18/18	Airex	USC 4200

All panels were fabricated using manufacturers' recommendations in conditions similar to a modern boatbuilding shop. This included vacuum-bagging or resin infusing all but the current laminate. To increase toughness by extending the resin cross-linking, all the panels were post-cured. Based on input from boat builders and material suppliers, the goal was to get as high a post cure temperature as possible without reaching the core's heat distortion temperature. This resulted in an eight hour post-cure at 140^{o}F.

From the fabrication standpoint there are several trade-offs to using one resin or core material over another and the shop personnel were asked to record the difficulty of using each material.

During fabrication the solvents in the vinyl ester resins (with the exception of the 8084) attacked the Airex core. Resin infusion appeared easier than hand lay-up, and some resins, notably the vinyl esters and ProSet epoxy "wet out" the fibers faster.

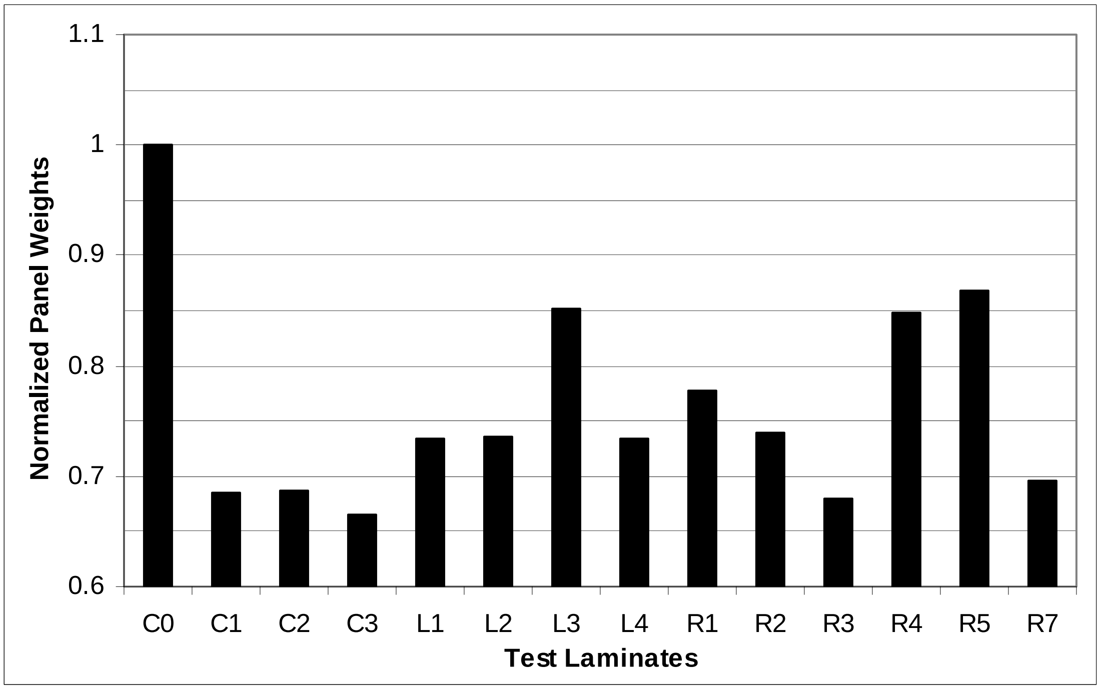
Weight Analysis and Print-Through

The Navy 44's are traditionally painted Navy Blue and require a high-quality surface finish. At the same time many resins exhibit a problem known as "print through" where the reinforcement fabric pattern can be seen through the paint. The main factors causing this are a high surface temperature caused by sun exposure on a hot day and coarse weave fabrics. Post-curing reduces this effect, as does a veil cloth. An epoxy-compatible veil cloth was not available. For these resins more fairing material was required to get a cosmetic surface.

Although gelcoat was a possibility, the advantages of post-mold inspection and the reality of annual touch-ups meant that painting was the better solution. Many of the panels required significant amounts of primer before being topcoated. The laminates that required the least painting preparation were the vinyl-ester resin laminates, which were built with a three-quarter ounce veil mat on the outer surface. The MAS epoxy laminate required the most preparation. All the panels were prepared and painted by the Naval Station Small Craft Repair Division staff to a glossy finish and then were placed in the Maryland summer sun. The ambient air temperature was 90^{o}F with a peak of 95^{o}F. Surface temperatures ranged from a low of 138^{o}F on panel L4 to a high of 158^{o}F on panel R5. Although the surface temperatures were over ten degrees above the post-cure temperature, no print-through was seen.

Panels were made using the base laminate of three plies of 18 oz/yd^2 fabric on each side of the core and various resin systems. Figure 2 shows the normalized, painted panel weights and illustrates that all the panels weighed less than the control panel. The difference between the predicted (using fiber volumes based on nominal cloth thickness) and actual weights was due to the beneficial vacuum-bagging pressure which resulted in lower resin contents. If extended to the full-size boat, the heaviest panels (the two vinyl-ester panels, R4 and R5, and the asymmetrical panel L3, would yield a savings of over 400 pounds. The greatest weight savings was with the USC 2000 resin, which would save up to 1000 pounds.

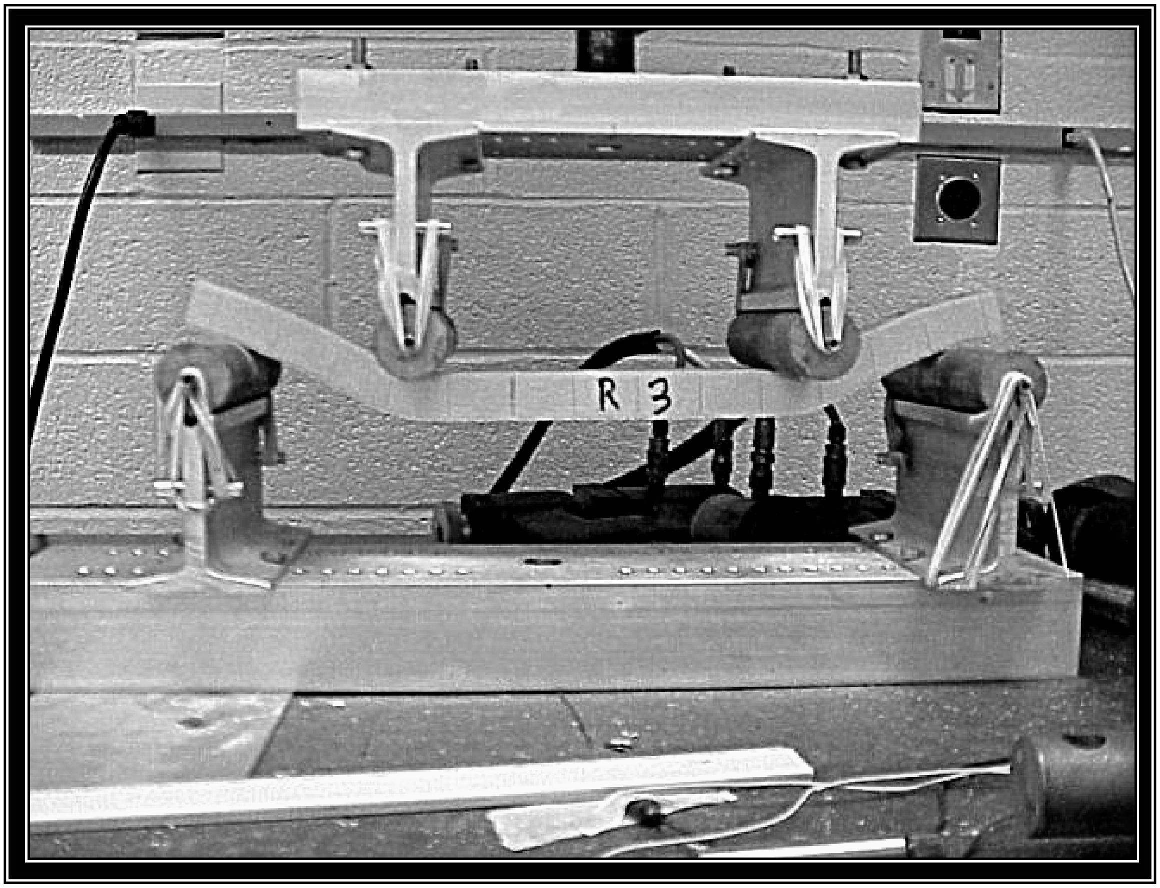
Figure 2: Normalized Panel Weights (with paint)



Flexural Coupon Tests

Both flexural strength and stiffness were design criteria for the new laminate, and to test flexural strength, 4-point bend coupons were compared in a SATEC UD50. In the flex test, a 1" x16" fiberglass coupon was placed on 1" diameter supports spaced fourteen inches apart with the tensile, or inside, skin down, as seen in Figure 3. A two thousand pound load cell with supports spaced nine inches apart was then lowered on the compressive (outside) skin.

Figure 3 – Four-Point Flex Test



Unlike many marine composites that are brittle, most of these coupons showed extensive plastic deformation, as seen in a Figure 4, which compares the 8084 vinyl ester with the most brittle epoxy 4200. The toughened nature of the Airex and CoreCell linear PVC cores and the high elongation resins were the reason. The plastic region did make determining the yield point more difficult and “yield” was defined in this case as a 50% reduction in the flexural modulus. As the strength-to-weight ratio is important for this design, the normalized specific flexural yield strength was calculated for each laminate and is shown in Figure 5.

Figure 4: Load - Deflection Curves For Toughest Vinyl Ester and Most-Brittle Epoxy

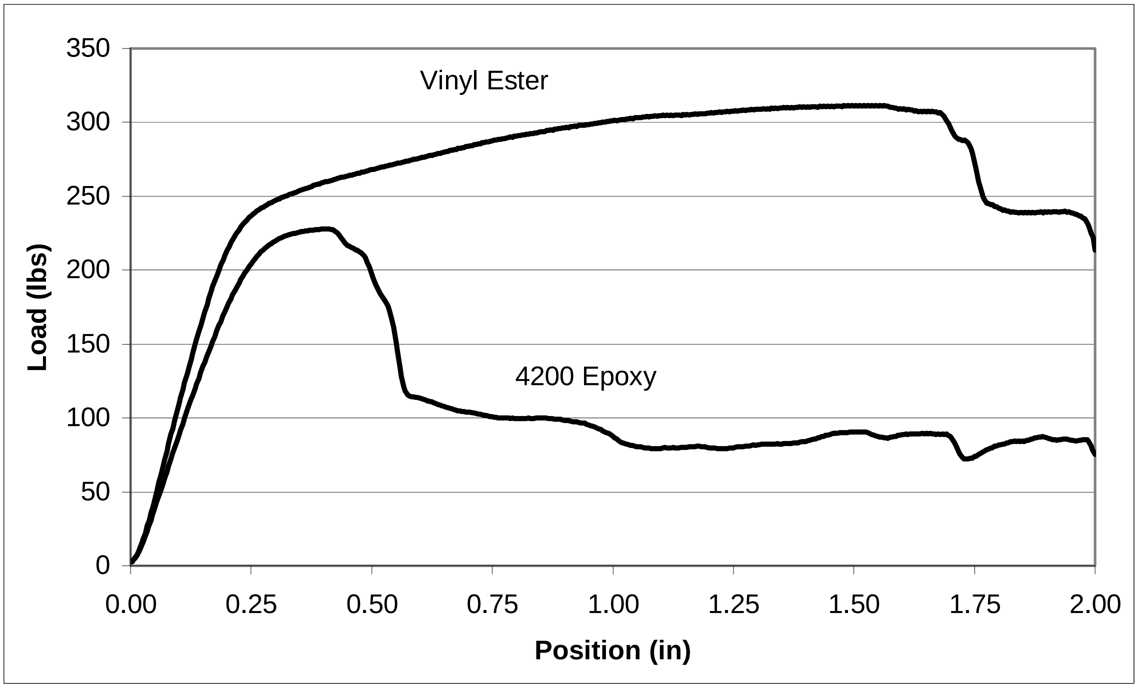
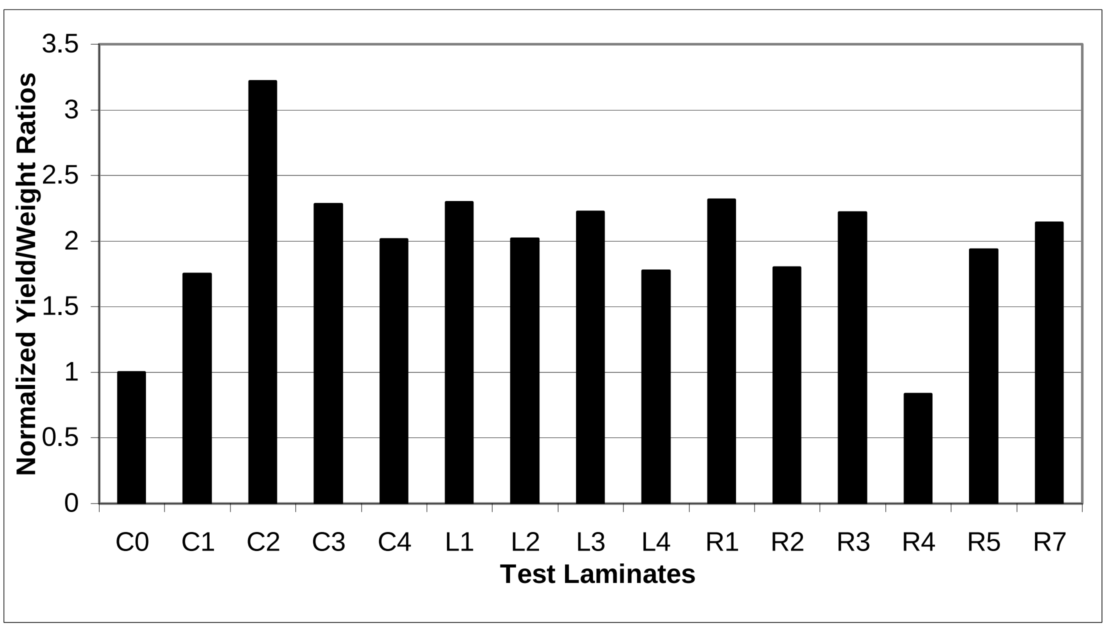


Figure 5: Normalized Flexural Yield

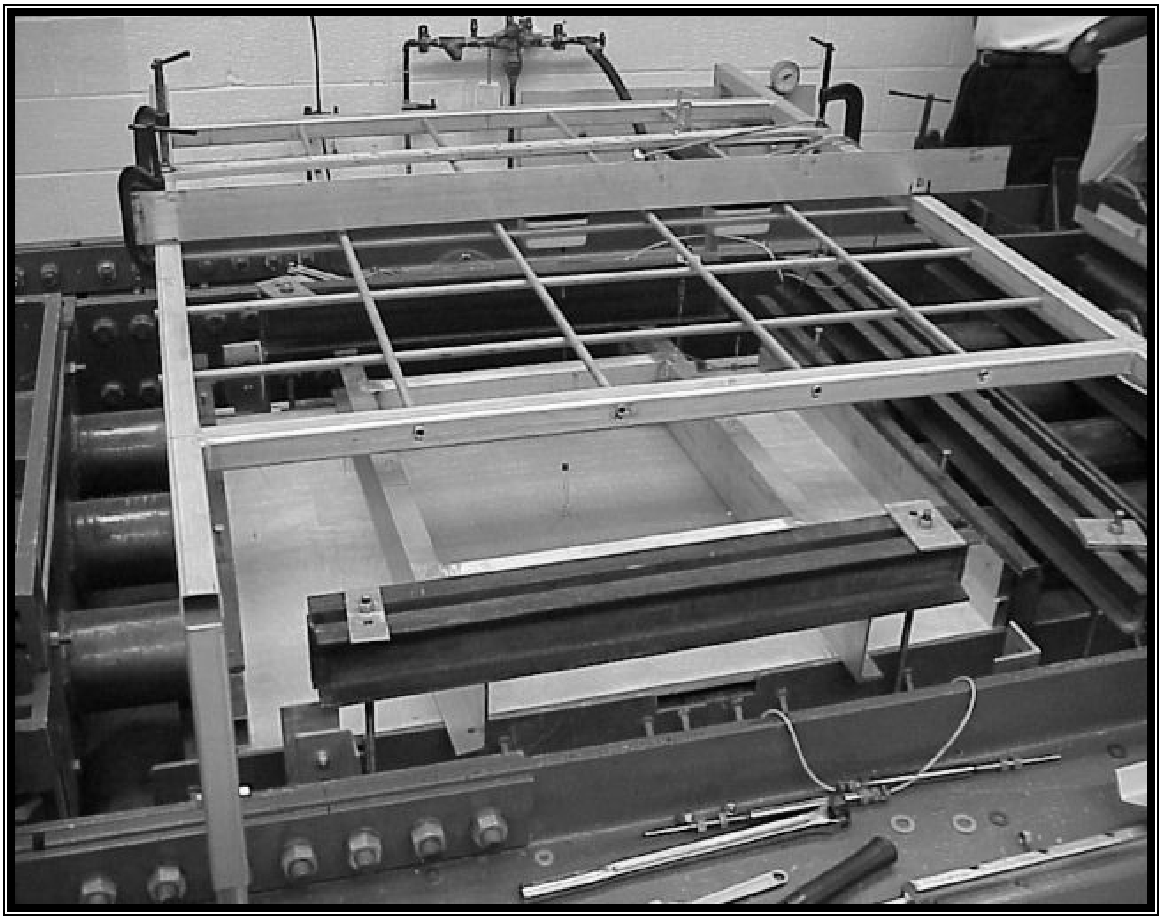


Of particular interest is the high value for the Divinycell core laminate. This cross-linked PVC showed high strength in quasi-static bending, but would show less desirable results in the impact tests. All laminates, except the Corezyn 8117 vinyl ester, showed improvement over the control. In most cases the new laminates showed between 50-100% improvement. Adding a Kevlar layer (L4 is C1 plus 5 oz Kevlar cloth) to both skins did not show a proportional increase in strength, and in fact, the nearly equal weight all-glass L1 laminate was significantly more efficient.

Panel Lateral Pressure Tests

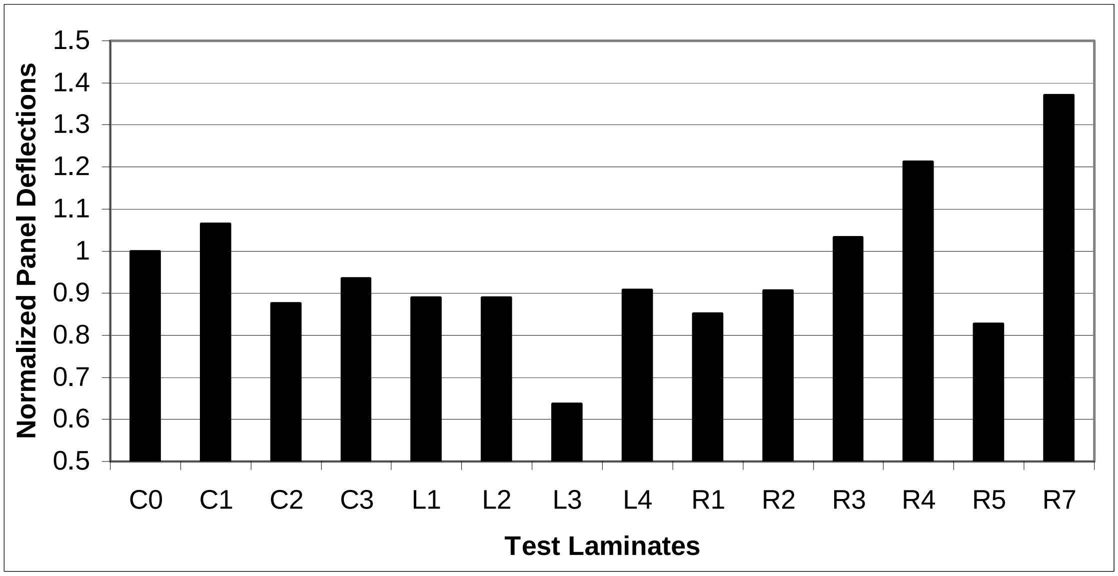
Although the 4-point bend tests gave an idea of stiffness and strength, edge effects were a concern due to the specimen geometry and ply orientation. Fibers oriented at 90^{o} to the bending coupon primary axis would not contribute to hull panel stiffness as much as they would in a square panel with simply-supported edges. A better simulation of the in-service condition would have lateral pressure applied to composite panels. In this project square panels (24 in x 24 in) were placed on a 15 psi water-pressure bag and were held in place by an aluminum frame. Deflections were measured using string-pots at the panel center and on the frame. Figure 6 shows the experimental setup.

Figure 6: Panel Pressure Test



Results from the pressure analysis showed similar stiffness trends for most laminates. Of the cores, Divinycel gave the stiffest laminate, followed closely by CoreCell. As expected, the laminate with the thickest skins, L3, had substantially greater stiffness. Of the resins, the Derakane 8084 vinyl ester and the ProSet 117 epoxy gave the stiffest laminate. Figure 7 shows the normalized results.

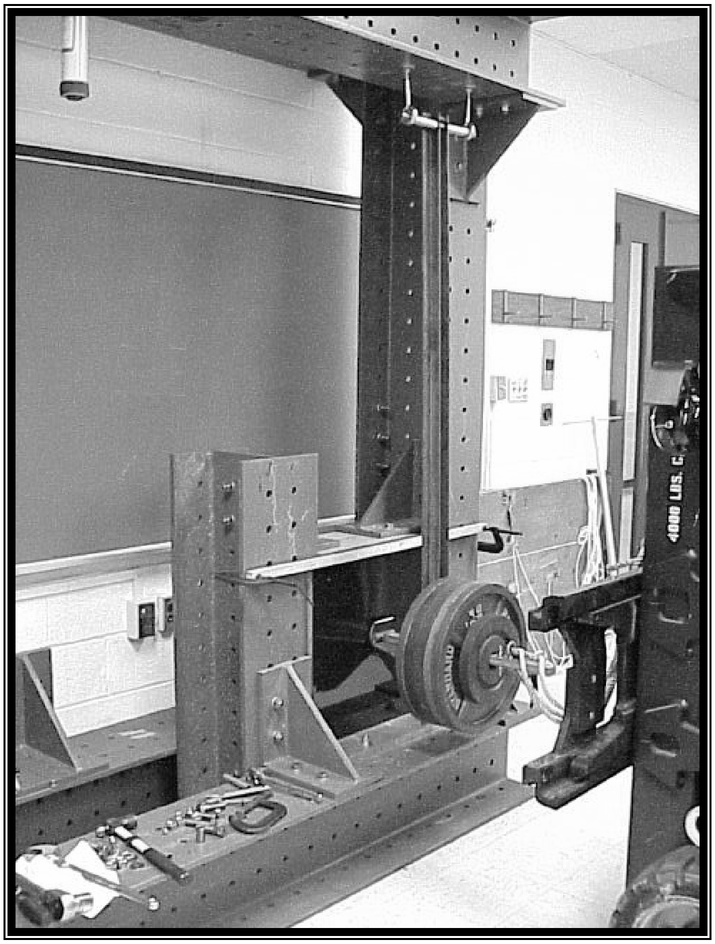
Figure 7: Normalized Deflections for Panel Tests



Impact Tests

The driving design criteria was impact toughness, therefore tests were performed simulating the collision of two Navy 44's. Abrate (1998) describes numerous impact test equipment that have been used, but to best simulate the in-service experience anticipated for these laminates, a steel replica of the first eight inches of the current Navy 44's bow was fabricated and attached to a six-foot swing arm assembly. Total weight of the impact head, arms, and weights was 306 pounds. Figure 8 shows the set-up before it was mounted to a more robust bracket and frame.

Figure 8 - Bow Impact Test Set-up



The initial impactor height was determined so that at impact the hammer speed was 8.5 knots. After release, the impactor was allowed to continue striking the panel until all energy was transferred. Although this created post impact damage, it did simulate the common collision situation where repeated impacts are produced by waves driving the hulls together. Maximum panel deflection was measured at the panel center using a stick gauge. Damage was determined by visual inspection of the surfaces and by cutting through the impact area to inspect the inner laminate and core. Table 3 describes the impact damage of each panel. Results of the impact test analysis agreed with some of the strengths seen in the 4-point bend tests and disagreed with others. Panel L3, the laminate with the most reinforcement fiber faired the best. It substantially outperformed the existing laminate and showed little surface damage. Both of the USC epoxy resin system panels, R3 and R7, showed laminate buckling, and the WestCore panel, C4, completely delaminated. The Kevlar/glass hybrid performed the same as the equal-weight all-glass laminate.

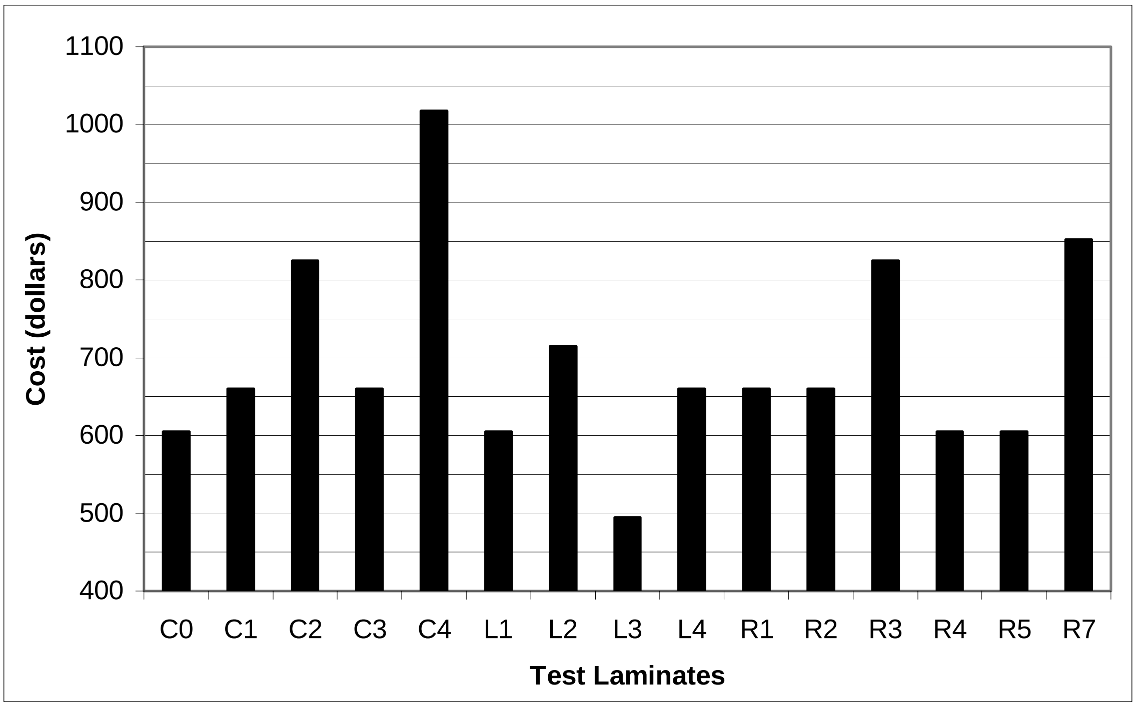
Table 3: Impact Damage

Laminate	Impact damage	Deformation (in)
C0	Local punch-through of compressive skin	0.25
C1	Local punch-through of compressive skin, local core damage	0.125
C2	Local core damage, buckling of compressive skin(vertical), delamination of compressive skin(along buckle line), minor punch-through of compressive skin	0.25
C3	Local punch-through of compressive skin, local core damage	0.125
C4	Severe core shear failure, delamination of compressive and tensile skins, tearing of both skins, local punch-through of compressive skin	N/A
L1	Local punch-through of compressive skin	0
L2	Local punch-through of compressive skin, unseen delamination of compressive side skin 2 inches wide in vertical direction	slight
L3	Core squished slightly, minor scratches on surface	0
L4	Local punch-through of compressive skin, local core damage	0
R1	Local punch-through of compressive skin, local core damage	slight
R2	Moderate to severe punch-through of compressive skin, local core Damage	0.25
R3	Local punch-through of compressive skin, buckling of compressive skin(horizontal and vertical) in lines radiating from impact area, 1/2 inch delamination of compressive skin in buckling area	0.375
R4	Local punch-through of compressive skin	0.125
R5	Local punch-through of compressive skin	0.25
R7	Major buckling of compressive skin(horizontal and vertical) in lines radiating away from impact area, line tear on tensile skin from edge in horizontal direction, 1 inch delamination in area of buckling Lines	0.25

Repair Cost Estimates

An important consideration for the Navy 44 is the ability to quickly and inexpensively repair the damage so as to return the vessel to service. The Naval Station provided repair estimates using a “shop rate” of $55/man-hour for each panel. An attempt was also made to determine “calendar” hours needed for each repair, but this proved to be too uncertain. Due to resin and paint curing and coating schedules, a minimum of three days was required for a repair. Figure 9 shows the repair estimates. In rough terms, values less than $600 would take three days, and $600-800 would take four days. The panels with costs exceeding $800 (C2, C4, R3, R7) could not be accurately determined as the damage extended to the panel edges. In an actual vessel the extent of damage could be significant, possibly including condemning the boat.

Figure 9: Estimated Panel Repair Costs



Conclusion

The basic project goals were met by identifying materials and laminates that would provide a lighter and more durable structure than the current laminate design. Additionally, due to the reduced number of plies and smaller amount of resin required, all the proposed laminates would also have a lower finished cost. Important conclusions that were verified included the confirmation that mat layers detracted from the strength of these toughened resin system laminates, and that small amounts of Kevlar gave the same performance as adding an equal weight of glass. CLT correctly predicted the stiffness and static strength trends, but did not give much insight into relative impact resistance of similar static strength laminates. More complex analytical methods specific to impact analysis are available but were not used in this study due to the uncertainty in the required material properties.

Between cores, either the Airex or CoreCell showed high impact toughness and would provide acceptable service. Of the resins, the vinyl ester with the best results was the Derakane 8084 due to its higher yield, greater stiffness and low repair cost. For similar reasons the best epoxies were the two ProSets. The vinyl esters were slightly less expensive and time-consuming to repair due to the veil cloth and curing method. Of the laminate skin weight, even the lightest skin, using 54 ounces of fabric on each side of the core would provide equal damage protection to the current laminate. The savings for this laminate would be over 1000 pounds (3.5% of the boat's displacement). If a tougher laminate is desired then a step up to 60 ounces of fabric per side makes sense. The final decision of which laminate to choose for the new boat would depend on other factors not considered in this study, such as the winning bidder's manufacturing methods. These might include whether vacuum bagging or resin-infusion was used.

The process used in this project could applied to similar material evaluations, however the specific results from this project should only be taken in context to the particular intended application.

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